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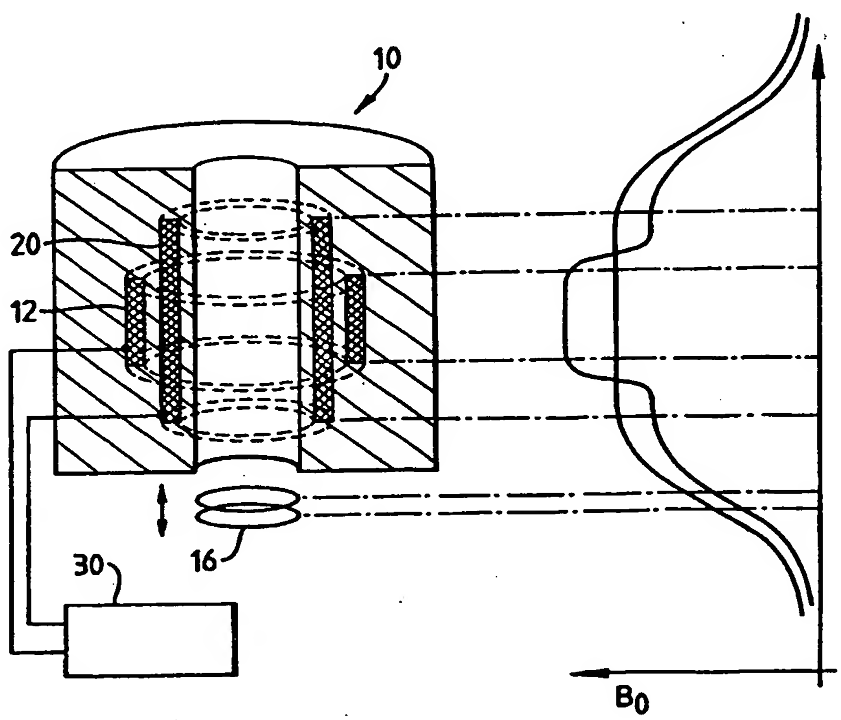
(54) Title: MAGNETIC RESONANCE IMAGING APPARATUS AND METHOD

(57) Abstract

Apparatus (and a method) is described for acquiring magnetic resonance imaging data for an object or region (16) under examination by means of the stray field associated with an NMR magnet (10) housing a main coil (20). In order to obtain data from different slices through the object or region (16) without the need for physical movement between the object or region and the NMR magnet (10), the stray field is varied to change its intensity profile in relation to the object or region. In one example, this is done by controlling the current applied to an additional coil (12) housed by the magnet and disposed either beside, outside or inside the main coil (20). The object or region of interest (16) may be located wholly or partially within either or both of the coils (12, 20), or may be disposed completely outside the magnet (10).



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MAGNETIC RESONANCE IMAGING APPARATUS AND METHOD

This invention relates to a magnetic resonance imaging apparatus and associated method, and it relates more particularly to such an apparatus and method utilising stray magnetic fields for imaging and thereby constituting a member of a class of such magnetic resonance imaging ("MRI") apparatus characterised as stray field imagers, or sometimes "STRAFI".

It has previously been shown that the stray magnetic field of a nuclear magnetic resonance ("NMR") apparatus, that is, the field outside the highly linear zone normally applied to an object to be imaged, can be used to image broad spectral line materials. Indeed, EP-0 399 789-A2 advocates the use of the gradient field for such purposes, pointing out that the stray magnetic field in an NMR apparatus, typically using magnets with a field strength of around 1 - 10 Tesla, can exhibit very significant magnetic gradient values, of the order of 0.1 Tesla per centimetre, well in excess of the gradients generated by conventional magnetic gradient field coils.

As is known, NMR imaging depends upon the selective excitation of molecular spins over a region of interest and this is achieved by the combination of a magnetic field of particular strength and bursts of radio frequency ("RF") energy applied with appropriate relative timing to selected areas of the region in a predetermined sequence. It is usual to employ gradient coils in three mutually perpendicular dimensions (x, y and z) to cause the applied field to vary with time and position over the region of interest, thereby allowing the collection of sufficient data for processing to generate the desired image.

The disclosure of EP-0 399 789 A discloses the use of such gradient coils to facilitate the conventional NMR Fourier transform-based imaging process. However, the conventional method for imaging samples placed in the stray field of a magnet involves the sample being physically moved relative to the field, and it is usual in such circumstances to mount the sample in a so-called probe, by means of which the sample can be accurately and controllably moved over relatively small distances relative to the field so as to successively position different portions (e.g. cross-sectional slices) of the sample at a location where the field assumes a selected intensity. Only molecular spins within the slice are excited by the aforementioned RF pulses and consequently are the

only ones to contribute to an induced signal. If relaxation effects are neglected then an induced signal is proportional to the number of spins within an imaged region. By acquiring data as the sample is moved completely through the imaging region a one dimensional profile of the sample can be built up from echo amplitudes.

An example of a probe for use with a STRAFI is described in US-A-5 424 644, which describes a device adapted to receive a sample and to displace it with respect to a magnetic field so that different portions of the sample are subjected at different times to a particular field strength provided by the gradient of the stray field. These probes are complex to manufacture and require elaborate control equipment, and it is an object of this invention to render unnecessary the physical movement of samples investigated by stray magnetic field imagers and further to do so without the need for conventional x, y and z gradient coils.

According to the present invention there is provided magnetic resonance imaging apparatus for imaging an object, comprising a field coil, having associated therewith a stray field exhibiting a characteristic profile, for establishing a region of resonance frequency within an object disposed in said stray field, and means for causing said profile to vary, thereby to effectively move the profile relative to the object.

In a preferred aspect the present invention provides magnetic resonance imaging apparatus comprising: a main field coil which generates a magnetic field gradient for establishing a region of resonant frequency within a sample to be imaged and means for varying the position of the magnetic field gradient with respect to the sample, so that the region of resonant frequency is displaceable with respect to the sample.

Preferably said field coil is the main field coil and said means for causing said profile to vary comprises a field sweep coil. The field sweep coil is preferably adapted to vary the magnetic field gradient of the main field coil, so as to establish a selectively displaceable net magnetic field gradient in the sample.

The field sweep coil may have a further stray field associated therewith exhibiting a respective characteristic profile.

Suitably the main field coil is capable of generating, within a given region of space, a substantially uniform magnetic field of sufficient intensity for stimulating magnetic resonance, and the characteristic profile of its stray field extends in a given direction from said region. Similarly, suitably the field sweep coil is capable of

generating an additional substantially uniform magnetic field within a given region, which may or may not overlap the given region for the main field coil, and the characteristic profile of its stray field may extend in the same given direction. The two stray fields in combination may exhibit a combined characteristic spatial variation of field intensity in the same direction.

This can enable the profile to be changed effectively and economically as the further field coil (called the "field sweep coil") can be supplied with current of amplitude significantly less than that supplied to the main field coil, such currents of lower amplitude being relatively easy to switch and control economically.

Preferably, the main and field sweep coils have coincident axes of symmetry.

The two coils may be disposed with one coil at least partially (and possibly fully) surrounding the other, or else they may, for example, be disposed (preferably spaced apart) in side-by-side relationship and in the latter case the two coils may be of the same diameter if desired. This can lead to magnet structures that are compact and/or convenient and economical to manufacture.

Preferably the apparatus is adapted, possibly by way of a suitable object support means, to accommodate the object at least partially within a volume enclosed by at least one of the coils (so that the region of interest lies within a volume within at least one of the field coils). Hence the object may be exposed to relatively large fields. This is not a necessary condition, however, and, where conditions permit or dictate, such as where a lower resonant frequency is used, the apparatus may be adapted to accommodate the object outside the volume enclosed by either coil (so that the region of interest may lie outside one or both of the coils). This latter arrangement particularly permits examination of objects or areas, access to all sides of which is not available.

In conventional NMR magnets great care is taken to ensure stability of the main (or central) field region and so it is generally not practical to change the field over the course of an experiment or whilst obtaining an image. Preferably the field sweep coil is a superconducting coil (possibly within the windings of an NMR apparatus), suitable for spectroscopy of very broad line materials and capable of effectively sweeping the characteristic profile through notional slices of the object. The field sweep coil may be capable of effectively sweeping the combined stray field step-wise through the object or region of interest, causing a combined stray field of selected strength to align in sequence

with different, slice-like, regions of the object; the combined gradient field having a sufficiently steep intensity characteristic at said selected strength to effect adequate resolution between adjacent slices.

Conveniently, the apparatus further comprises means for supporting the object relatively stationary whilst the apparatus is in operation. Thus preferably the sample to be imaged may be held relatively stationary, with respect to the aforementioned coils in an NMR probe, outside any net homogeneous magnetic field, while current in the main or the field sweep coil is varied. This can ensure that there is no uncertainty of position brought about by problems such as backlash, which can arise from the use of variable positioning mechanisms.

Advantageously, the gradient of the characteristic profile is arranged to be substantially constant throughout said region. Preferably said region is located at a position where the field strength of the stray field is approximately half its maximum (central) value. In such an arrangement it is possible to image a different portion of a region of interest of the sample by increasing or decreasing the main field of the magnet.

The region of interest may be in the form of a slab with its shortest dimension parallel to the main magnetic field and may usually be located at a position near to one end of a superconducting magnetic field coil.

The supply of current to either the field sweep coil or the main field coil (or both) may be varied so as to vary a net magnetic field gradient, in other words so as to change the characteristic of the combined stray field to image different portions of a region of interest of the sample.

Hence preferably said means for causing said profile to vary further comprises means for varying the current in said field sweep coil. The means for varying the current may be adapted to vary such current in predetermined steps. Thus preferably the position of a magnetic gradient field generated by a first current supplied to a main field coil is varied by supplying a second current to a field sweep coil so as to displace a region of resonance within a sample to be imaged.

Alternatively or additionally said means for causing said profile to vary may further comprise means for varying the current in said main field coil.

When the current is varied in the field sweep coil, a back emf is generated in the main field coil, so there does tend to be some interdependence associated with changing

the supply of current to either coil. By changing the current in the main field coil, the two generated magnetic fields, from the field sweep and main coils, can be superimposed.

The current through the sweep field coil is conveniently increased step-wise during a sweep from zero to a maximum value, which may amount to several Amps (although these values may be changed if it is desired to image different materials). As this current is increased, the central magnetic field associated with the magnet containing both coils starts to increase. However, because of the mutual inductance (typically of the order of a few Henries) associated with each of the coils, the current in the main coil is reduced. Thus, although the central (substantially uniform) field increases, the stray field decreases. This causes the field strength associated with resonance in a selected slice of the object or region of interest to move towards the central region of the magnet as the central magnetic field strength increases.

Thus the technique works by varying the position of a resonance condition while keeping the magnetic gradient field fairly constant.

By avoiding the need for physical movement of an object under investigation relative to the magnetic fields, the invention exhibits the advantage of avoidance of the problems associated with such physical movement, notably the requirements for positional reproducibility, and lack of backlash or travel misalignments.

The present invention extends to a method of magnetic resonance imaging an object, comprising providing a field coil having associated therewith a stray field exhibiting a characteristic profile, disposing the object in said stray field, establishing a region of resonance frequency within the object, and causing said profile to vary, thereby to effectively move the profile relative to the object.

Preferably the object is not moved relative to the field coil.

The present invention also preferably extends to a magnetic resonance method wherein a field coil system is used to generate a magnetic field gradient for establishing a region of resonance frequency within a sample to be investigated, and the position of the magnetic field gradient is varied with respect to the sample.

In order that the invention may be clearly understood and readily carried into effect, preferred features thereof will now be described, by way of example only, with reference to the accompanying drawings, of which:

Figures 1a, 1b and 1c show diagrammatically various magnetic coil arrangements

for apparatus in accordance with various embodiments of the invention;

Figure 2a shows a particular sample geometry and disposition;

Figure 2b is a graph obtained in relation to the sample of Figure 2a by means of a conventional, STRAFI technique wherein the sample was physically moved relative to the stray field; and

Figure 3a and 3b are graphs obtained in relation to different locations of a sample by means of the invention.

Referring now to the drawings, Figures 1a, 1b and 1c show respectively different magnet and coil configurations. In each of these figures, a Magnex (trade mark) generates a main (substantially uniform) magnetic field of 7.04 Tesla by means including a main field coil 20 disposed in an 89mm vertical bore magnet 10.

In Figures 1a and 1c, the magnet 10 also contains an internal superconducting field sweep coil 12 which, in this example, is capable of increasing the main magnetic field by the order of 0.5 Tesla. The field sweep coil 12 surrounds part of the main coil 20 in the arrangement shown in Figure 1a, whereas the arrangement of Figure 1c has the two coils 20 and 12 in spaced, side-by-side relationship and of equal radii. In both cases the coils 20 and 12 are coaxial.

In the case of both Figure 1a and Figure 1c, there is shown schematically a sample 16 which is located in the stray field of the magnet 10, this representing of course the combined stray fields associated with the coils 20 and 16. In each case, the sample 16 is shown as being located at a position where the stray field gradient is significant and consistent, and where the absolute strength of the stray field is about one half of that of the substantially uniform field established within the magnet.

It will be seen that the characteristics of the stray field vary in a direction axial of the magnet 10 (the z direction), and that the stray field may be effectively shifted in that direction to sweep the characteristic through the sample, sequentially aligning that part of the characteristic indicative of a stray field of a given strength with different regions or slices of the sample. Thus, successive slices of the sample can be made the subject of NMR examination without the need for any physical movement of the slice, merely by changing the stray field characteristic, and this is most conveniently done by changing the current applied to the field sweep coil 12, via current controller 30 (see Figure 1a) which can also control the current to the main field coil. The current is

preferably changed step-wise, for example from zero to 18 Amperes in steps of one Ampere; each step effectively positioning the characteristic so that the stray field intensity required for spin excitation occurs in a different slice of the sample.

Conventional transmitter and receiver circuitry can be utilised to excite the spins and measure their relaxation. In this example it is preferred to use a Chemagnetics CMX Infinity (Trade Mark) spectrometer (not shown) to provide the transmitter and receiver electronics.

It will be noted that Figure 1b shows the magnet 10 containing only the main coil 20. This is to indicate that, if desired, the z direction component of the stray field characteristic can be varied without the use of a field sweep coil by suitably controlling the current supplied to the coil 20. This expedient may, of course involve the control of the very large currents supplied to the coil 20 (typically several tens of Amperes), which can in some circumstances cause difficulty and require expensive circuitry.

As can be seen from Figures 1a and 1c, the sample can be located completely outside the bounds of the magnet 10, or may be disposed at least partly within the magnet. In the latter case, the sample may lie wholly or partially within the axial extent of one or both of the coils 20 and 12, depending on a number of factors including the nature of the sample, the molecules under investigation and the environment in which the examination takes place.

It has previously been stated as being known that the sample 16 can be physically moved relative to the magnet 10 in order to acquire NMR data from a stray field analysis. Figures 2a and 2b show respectively a particular sample of closely defined dimensions disposed at a well defined attitude with respect to the magnet and a graph illustrating some results obtained in respect of that sample when it was moved, in accordance with the prior art, along the z direction relative to the magnet. This graph will be compared with graphs shown in Figures 3a and 3b, illustrating results obtained by means of the present invention.

The sample 16 may be moved (as conventionally) through a sensitive slice as shown in Figure 2b, or resonance conditions may be moved through the sample 16 by varying the central field as shown graphically in Figures 3a and 3b.

Referring to Figure 2a, the sample 16 comprises a short square-section length of polymethyl methacrylate (PMMA) or Perspex (Trade Mark) with nominal dimensions 3.5

x 3.5 x 8.5 mm; it has been machined to fit within a 7.5 mm sample tube/bore of an NMR probe (not shown), where it is placed for movement, relative to the magnet 10, along the z axis. The longitudinal axis of the sample was orientated at an angle of 54 degrees, 44 minutes to the main B_0 field, as shown in Figure 2a. The sample was placed at a distance of 0.27 m from the centre of the magnet 10 where the resonant frequency for protons was found to be 120 MHz.

Referring to Figure 2b, the sample 16 was moved through a sensitive region of the magnet along the z direction in steps of 1 mm, each step aligning a different slice through the sample with the stray field strength associated with that frequency. Echo data acquired in this way were used to construct a one-directional profile of the sample, and this is shown graphically in Figure 2b. The points show the experimental data, while the solid line shows an empirical fit to the known sample profile, when orientated as was the sample.

The same sample was then mounted in a static mount in order to determine the degree of resolution possible using the field swept STRAFI technique of the present invention.

Sweep coil 12 was supplied with current which was increased from zero to 18 Amperes in steps of one Ampere and a one-dimensional profile of the sample 16 at a fixed position was produced. In fact, profiles of the sample 16 were acquired at two separate positions (26.5 and 26.7 cm respectively from the magnet centre) along the sample length. The first position corresponded with a uniform (cross-sectional) length of the sample, where a constant echo intensity would be expected, and the results are shown graphically in Figure 3a. The second position embraced an end of the sample, where the change in sample profile was expected to give rise to a decrease in signal intensity, these results being illustrated in Figure 3b.

An RF pulse of 5 microseconds duration was used for both positions, with an inter-pulse spacing of 30 microseconds. The echoes were acquired at a bandwidth of 5 MHz with 256 sample points. The self-inductance of the main field coil, L_M, was 51.6 H and that of the sweep coil, L_S, was 4.48 H. Their mutual inductance, M, is 9.07 H.

As the field sweep coil 12 was energised current in the main field coil was reduced as energy is conserved, as represented by Equation 1

$$\frac{1}{2}L_M i_M^2 + \frac{1}{2}L_M i_S^2 = \frac{1}{2}L_M i_m^2 + M i_m i_S + \frac{1}{2}L_S i_S^2 \qquad \textit{Eqn}.1.$$

where i_M is the initial main coil current, i_m is the final main coil current and i_S is the final sweep coil current.

The reduced current in the main coil is then given by Equation 2.

$$i_m = -\frac{M i_S}{L_M} + \sqrt{\left(\frac{M i_S}{L_M}\right)^2 + i_M^2} \qquad \textit{Eqn}.2$$

The magnetic gradient at the point where the measurements were made was measured to be 40 ± 0.5 Tm^{-1} using a Hirst GM04 (Trade Mark) "Gaussmeter" (not shown) fitted with an axial Hall probe (not shown). When the field sweep coil 12 was energised to the maximum current used, the initial main coil current of i_M = 96.3 A was reduced to a final current of i_M = 93.2 A.

To a first approximation it was assumed that the resonant frequency near the region of interest was proportional to the current in the main field 20 coil of the magnet 10 and that the frequency would decrease from 120 MHz to approximately 116 MHz, a decrease of 4 MHz. With a constant gradient over the region of interest the 120 MHz position shifts by approximately 2 mm towards the centre of magnet 10. This may be compared to a measured signal decrease from the known sample geometry. Measurement at the edge of the sample 16 was made at a distance of 26.7 cm from the magnet centre. The expected sample profile at this point is known from the measurements taken (and depicted in Figure 2a) while the sample 16 was moved manually through the sensitive plane and from the position of the sample within the probe assembly. The profile produced from this field sweep experiment was compared to the known sample profile obtained previously. The field sweep experiment has a measured sensitivity of 13 ± 0.5 A mm^{-1} giving a working range of ~1.4 mm over the full current range of the sweep coil. This agreed well with the value predicted from the calculated change in the current through the main field coil 20.

Thus the results show that it is possible to use a modified stray field imaging technique to image samples without having to physically move them through the sensitive

slice.

In summary, in the preferred embodiment apparatus (and a method) is described for acquiring magnetic resonance imaging data for an object or region 16 under examination by means of the stray field associated with an NMR magnet 10 housing a main coil 20. In order to obtain data from different slices through the object or region 16 without the need for physical movement between the object or region and the NMR magnet 10, the stray field is varied to change its intensity profile in relation to the object or region. In one example, this is done by controlling the current applied to an additional coil 12 housed by the magnet and disposed either beside, outside or inside the main coil 20. The object or region of interest 16 may be located wholly or partially within either or both of the coils 12, 20, or may be disposed completely outside the magnet 10.

The present invention is well suited for experiments where it is impractical to move the sample during the time-scale of the experiment and where the region of interest is of the order of 1 mm, e.g. thin films, surface effects or boundary layers.

It will be appreciated that the present invention has been described by way of an example only, and variation to the aforementioned embodiment may be made without departing from the scope of the invention.

CLAIMS

1. Magnetic resonance imaging apparatus for imaging an object, comprising a field coil, having associated therewith a stray field exhibiting a characteristic profile, for establishing a region of resonance frequency within an object disposed in said stray field, and means for causing said profile to vary, thereby to effectively move the profile relative to the object.

2. Apparatus according to Claim 1 wherein said field coil is the main field coil and said means for causing said profile to vary comprises a field sweep coil.

3. Apparatus according to Claim 2 wherein the field sweep coil has a further stray field associated therewith exhibiting a respective characteristic profile.

4. Apparatus according to Claim 2 or 3 wherein the main and field sweep coils have coincident axes of symmetry.

5. Apparatus according to Claim 2, 3 or 4 wherein the main and field sweep coils are disposed with one coil at least partially surrounding the other.

6. Apparatus according to Claim 2, 3 or 4 wherein the main and field sweep coils are disposed in side-by-side relationship.

7. Apparatus according to Claim 6 wherein the two coils are of substantially the same diameter.

8. Apparatus according to any of Claims 2 to 7, being adapted to accommodate the object at least partially within a volume enclosed by at least one of the coils.

9. Apparatus according to any of Claims 2 to 7, being adapted to accommodate the object outside the volume enclosed by either coil.

10. Apparatus according to any of Claims 2 to 7 wherein the field sweep coil is a

superconducting coil, suitable for spectroscopy of very broad line materials and capable of effectively sweeping the characteristic profile through notional slices of the object.

11. Apparatus according to any of the preceding claims further comprising means for supporting the object relatively stationary whilst the apparatus is in operation.

12. Apparatus according to any of the preceding claims wherein the gradient of the characteristic profile is arranged to be substantially constant throughout said region.

13. Apparatus according to Claim 12 wherein said region is located at a position where the field strength of the stray field is approximately half its maximum value.

14. Apparatus according to any of Claims 2 to 13 wherein said means for causing said profile to vary further comprises means for varying the current in said field sweep coil.

15. Apparatus according to Claim 14 wherein the means for varying the current is adapted to vary such current in predetermined steps.

16. Apparatus according to any preceding claim wherein said means for causing said profile to vary further comprises means for varying the current in said main field coil.

17. A method of magnetic resonance imaging an object, comprising providing a field coil having associated therewith a stray field exhibiting a characteristic profile, disposing the object in said stray field, establishing a region of resonance frequency within the object, and causing said profile to vary, thereby to effectively move the profile relative to the object.

18. A method according to Claim 17 wherein the object is not moved relative to the field coil.

19. Magnetic resonance imaging apparatus for imaging an object substantially as herein described with reference to and as illustrated in the accompanying drawings, with

the exception of Figure 2b.

20. A method of magnetic resonance imaging an object substantially as herein described.

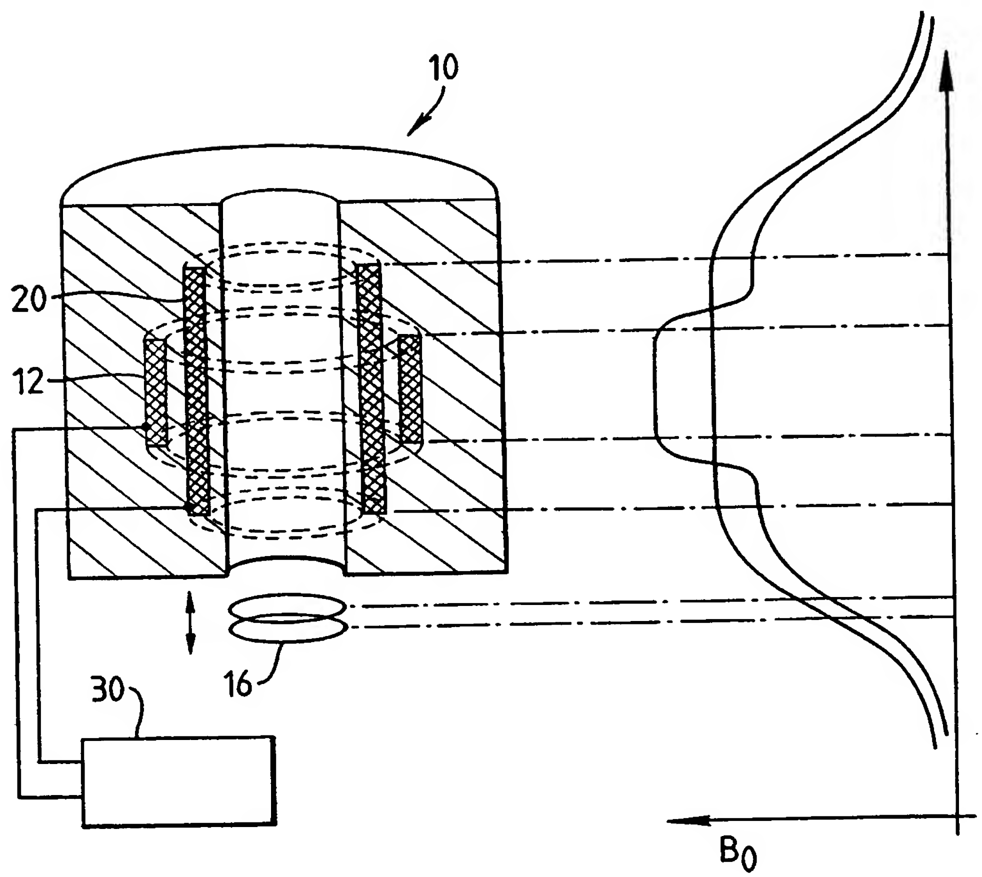

Fig. 1a

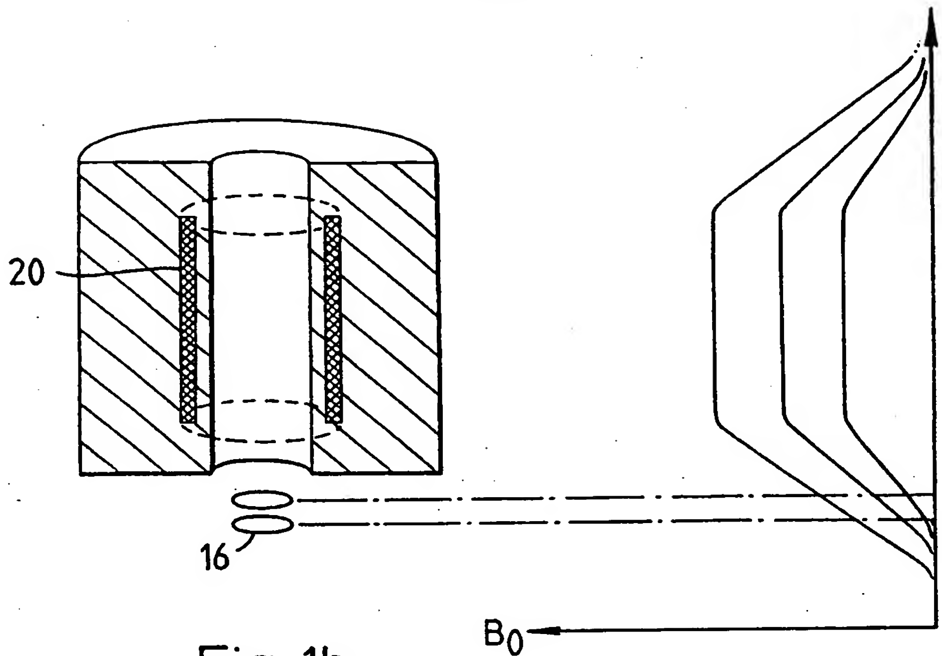

Fig. 1b

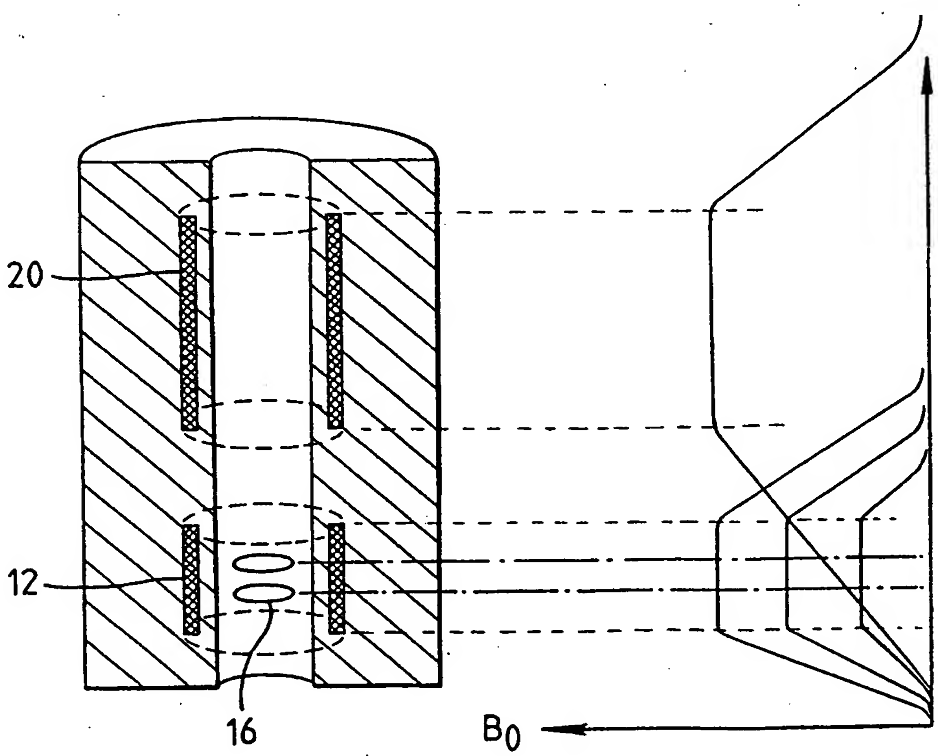

Fig. 1c

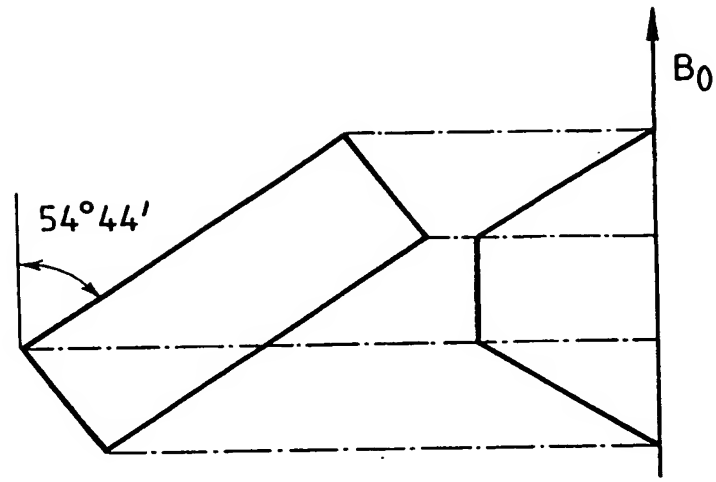
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Fig. 2a

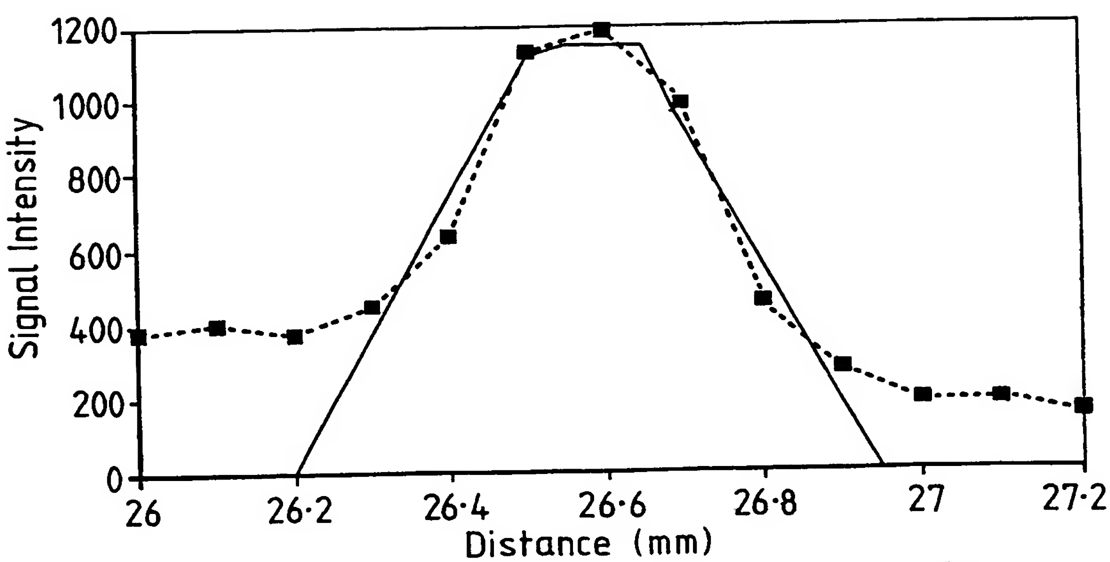
1200
1000
800
600
400
200
0
Signal Intensity
26
26·2
26·4
26·6
26·8
27
27·2
Distance (mm)

Fig. 2b

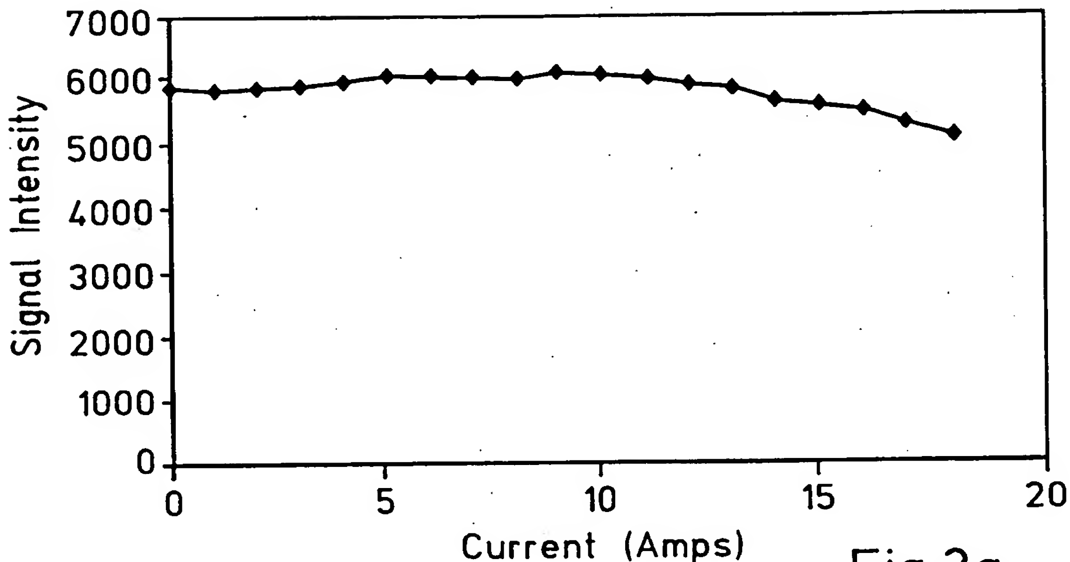
7000
6000
5000
4000
3000
2000
1000
0
Signal Intensity
0
5
10
15
20
Current (Amps)

Fig.3a

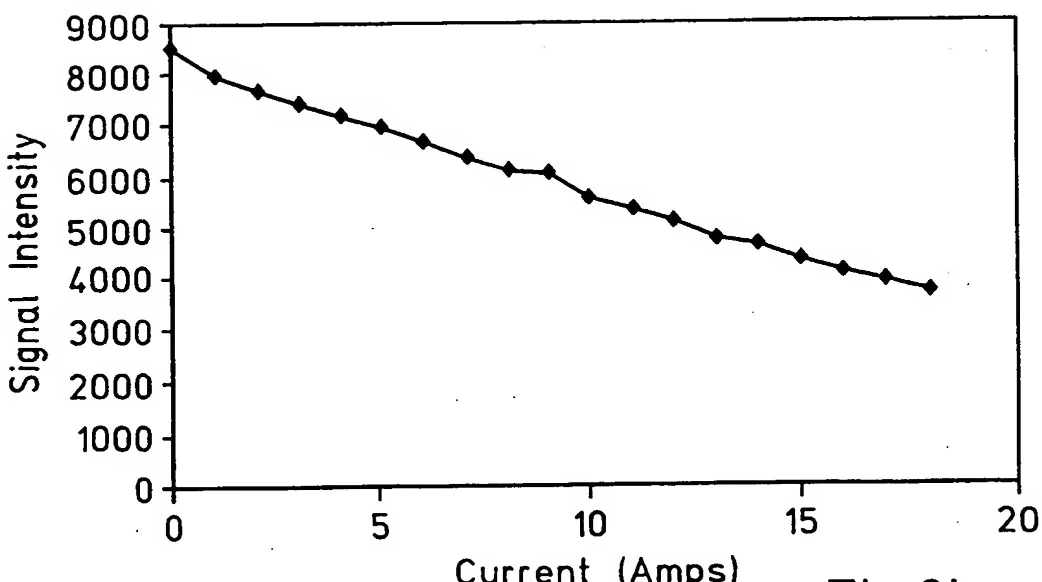
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Signal Intensity
0
5
10
15
20
Current (Amps)

Fig.3b

INTERNATIONAL SEARCH REPORT

International Application No
PCT/[illegible] 98/00902

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G01R33/38

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 G01R

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 0 512 345 A (BRUKER INSTRUMENTS, INC.) 11 November 1992 see column 3, line 33 - column 10, line 21 see figures 1-4 ---	1,2, 9-12,14, 15,17,18
X	A.M. BLAMIRE ET AL.: "Dynamic Shim Updating ..." MAGNETIC RESONANCE IN MEDICINE, vol. 36, 1996, pages 159-165, XP000593575 see page 159: abstract see page 159, last paragraph - page 163: 2nd paragraph --- -/--	1-5,7,8, 11,12, 14,15, 17,18

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
7 July 1998	14/07/1998

Name and mailing address of the ISA	Authorized officer
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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

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X	US 5 390 673 A (D. KIKINIS) 21 February 1995 see column 2, line 24 - line 66 see column 4, line 41 - column 6, line 12 see figures 1-5 ---	1-3,9, 11,14, 15,17,18
X	WO 92 07279 A (OXFORD INSTRUMENTS LIMITED) 30 April 1992 see page 2, line 23 - page 4, line 14 see page 5, line 23 - page 6, line 12 see page 7, line 1 - line 25 see figure 1 -----	1,2,17

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I[illegible]tion on patent family members

Int[illegible] Application No
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